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Analysis of bioengineered concrete for use in a submerged reef type breakwater

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ANALYSIS OF BIOENGINEERED CONCRETE FOR USE IN A SUBMERGED REEF TYPE BREAKWATER

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ABSTRACT

The oysterbreak is a method of growing an oyster reef into a wave attenuating device. A study was conducted to determine an optimal material for the oysterbreak. As oysters grow on the oysterbreak, wave energy in the lee of the structure is reduced. It was predicted that more rapid oyster growth would lead to a more rapid reduction of wave energy. Louisiana is losing coastal marshes at an alarming rate. Wave action from storms erodes sediments from Louisiana's shorelines and barrier islands. Structures such as the oysterbreak may be used to protect Louisiana's fragile shorelines. A material for the oysterbreak may also be used to produce artificial oyster reefs or harvestable oyster cultch.

Concrete makes an excellent structural material and is attractive to oysters. It was hypothesized that adding cottonseed or crushed oyster shell to concrete would stimulate greater oyster growth than on concrete alone. The objectives of this study were to 1) determine whether concrete containing either cottonseed or oyster shell would have a greater increase in cross section due to oyster growth compared to concrete with no biological additive and 2) determine the structural properties of concrete with increasing amounts of cottonseed. Concrete samples were deployed in Caminada Bay near Grand Isle Louisiana in June of 2005. By March of 2006, concrete with oyster shell experienced the most growth (16.2% increase in perimeter of the bar), followed by samples with cottonseed (11.2% increase in perimeter). Samples with no additive had the least oyster growth (7.9% increase in perimeter).

An experiment was also conducted to determine the structural properties of concrete with cottonseed in it. Density ranged from 2.25 g/cc for samples with no cottonseed to 2.05 g/cm^3 with samples with a high concentration of cottonseed. Strength ranged from 27 MPa for samples with no cottonseed to 7 MPa for samples with the highest concentration of cottonseed. It was

determined that this range of strength was acceptable for use in the oysterbreak. It was also concluded that concrete containing either cottonseed or oyster shell would make a superior material for the oysterbreak, compared to concrete alone.

INTRODUCTION

Louisiana's coast has been experiencing rapid land loss and is losing coastal wetlands at a rate of 65-90 square kilometers per year (Coast 2050). The average short term rate of shoreline erosion is 9.4m/yr, up from a long term average of 6.1m/yr (Penland et al. 2005). Rapid subsidence, eustatic sea level rise, marsh channelization and drastic alteration to the natural Mississippi River building processes are the main reasons for this accelerated land loss (Hatton et al. 1983). Storm events, such as the hurricanes of 2005, create high energy waves and washover events that breach beaches and barrier islands. These features recover during fair weather conditions, but not to their original conditions (Penland et al. 2005). Similar problems (though not necessarily of the same magnitude) occur along the coasts of Texas (Rodriguez et al. 2001) and other gulf states.

Breakwaters

Breakwaters have been used to stop or reduce wave action reaching a shoreline, thus reducing or even reversing erosional losses. The reduction in wave energy slows littoral drift, induces sediment deposition, and creates a shoreline bulge in the lee of the structure (CEM V-3). Breakwaters can be either emerged or submerged. Emerged breakwaters are designed to completely stop wave energy in the lee. Submerged structures are used where total wave energy reduction is either not practical (i.e. too expensive) or not desirable (Ahrens 1987). The United States Army Corps of Engineers provides guidelines for predicting shoreline response based relationships between the structure and the beach (CEM VI-5). Other studies suggest methods for predicting the structure's effects on incoming waves (Ahrens 1987). The effects on incoming waves are described by three ratios: 1) wave transmission number, K_t, 2) wave reflection number, K_r, and 3) wave dissipation number K_l. The wave transmission number, K_t, is the ratio of the wave height in the lee of a breakwater to the incident wave height. It describes the amount of wave energy that passes through a structure. The wave reflection number K_r, is calculated as the square root of the ratio of reflected wave energy to incident wave energy. The wave dissipation number describes wave energy that is lost due to friction and other factors (Ahrens 1987).

Campbell (2004) suggested a method to grow an oyster reef into the shape of a submerged breakwater. The method consists of placing a light weight support structure into the near shore area on which the oysters can grow. The structure has been designed with materials to stimulate oyster growth, and a shape to allow the oysters to dissipate wave energy. As the oysters grow, the structure will become completely dominated by the oyster reef. The structure has been termed "oysterbreak". A physical model study concluded that the oysterbreak effectively reduced wave action in the lee of the structure (Campbell 2004). As growth occurred on the structures, performance approached that of Ahrens's predictive model (Ahrens 1987). Finally, Campbell (2004) developed a model for predicting the wave transmission number, K_t, with time based on structural geometry and rates of oyster growth. As the oysters fill in spaces in the oysterbreak, the wave transmission number decreases until it approaches the wave transmission number predicted by Ahrens (1987). One possible configuration of the oysterbreak consists of placing hexagonal units adjacent to, and on top of each other to achieve a desired geometry (Figure 1). In this configuration, the hexagonal units are 182.2 cm along the longest axis. The cross sections of the elements of the hexagon have dimensions of 15.24 cm by 15.24 cm. The face of the hexagon has a cross sectional area of 1.25 m^2. Each unit has a volume of 205,800 cm^3.

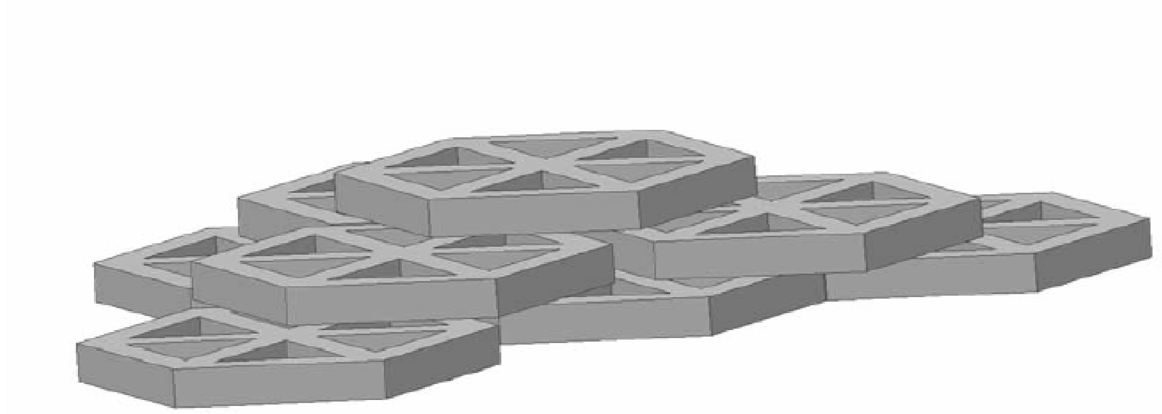

Figure 1: Concrete hexagonal units are stacked to create an oysterbreak. In this example, the oysterbreak is approximately 0.5 meters tall and can be built to various lengths and widths.

The Eastern Oyster

The eastern oyster, *Crassostrea virginica,* is a sessile invertebrate bivalve commonly found in estuarine waters with a salinity above 5 to 10 parts per thousand (ppt), and is most abundant where salinity ranges between 10 and 20 ppt. Oysters thrive at salinities above 20 ppt, however predation is heaviest in these areas (Kennedy 1996; Shumway 1996). The oyster is very temperature tolerant and can be found from the Western Gulf of Mexico to Canada (Shumway 1996). The most critical areas for oyster habitation are oyster beds formed by the accumulation of shells over the course of many years, though oysters do frequently colonize fossilized shell beds and accumulations of other mollusk shells (NCDMF 2001). Oysters have also been known to settle on exposed roots at the fringes of *Spartina* marshes and on pilings, seawalls, and other manmade structures (NCDMF 2001).

The oyster begins life as a free swimming, planktotrophic larva. Larvae are distributed primarily by water currents, but are capable of swimming vertically at speeds up to 2mm s^{-1}. Oysters at this stage suffer a high mortality rate due to predation, and possibly poor food supply. Larvae that survive the pelagic stage eventually reach the benthic stage. Now called pediveliger larvae, these oysters crawl with a ciliated foot, searching for chemical cues. If conditions are right, pediveliger larvae will cement to the hard substrate (i.e. cultch) and metamorphoses into juvenile oysters or "spat" (Kennedy 1996) in a process known as "setting." Once set, an oyster can reach market size (>90mm) in 2-5 years, depending on temperature (Shumway 1996). It has been shown that some oysters in Louisiana can reach this size in less than 9 months (Menzel 1951). In southern waters, oysters can grow throughout the year. In colder areas, growth is limited to 7 or 8 months of the year (Shumway 1996).

The eastern oyster is a dioecious protandic hermaphrodite. It is sexually undifferentiated for part of the year, and then develops gonads as spawning season approaches. Spat typically develop gonads 8 to 12 weeks after settlement. Spat are usually male in the first year, though factors such as temperature, health, and male/female ratio can influence this (Eble et al. 1996). The spawning period of the eastern oyster varies with location. In the Gulf of Mexico, spawning lasts from May until late October. In the Chesapeake Bay, spawning lasts from early June until October, and farther north, only lasts from June until August. The geographical and seasonal nature of oyster spawning indicates that temperature has a significant effect on spawning (Thompson et al. 1996). In fact, spawning can be triggered in hatcheries by increasing the temperature of the water (Castagna et al. 1996). After spawning, and the gonad reenters the indifferent stage the oyster begins a period of glycogen storage, commonly called "fattening." Depending on location, the oyster will either continue to build glycogen stores throughout the winter, or metabolize its glycogen stores when it is too cold to feed. Glycogen stores reach a peak immediately before gametogenesis, and are practically depleted by the end of the spawning season (Thompson et al. 1996). Juvenile oysters are ready to set shortly thereafter.

A variety of physical factors affect setting. Increased temperature has been shown to stimulate setting, but not salinity (Kennedy 1996). Larvae are negatively phototrophic and tend to settle on shaded surfaces. They have also been shown to prefer highly irregular or pitted surfaces. Oysters are very gregarious. It has been shown that they will almost inevitably select a surface near other oysters, probably due to a waterborne pheromone (Kennedy 1996). Oyster larvae are also highly influenced by the presence of a biofilm (Anderson 1995). It has been shown that certain bacteria in naturally occurring biofilms produce chemical messengers such as L-3-4-dihydroxyphenylalanine (L-DOPA) and melanin that stimulate setting (Kennedy 1996). It has also been shown that ammonia (NH_3) induces settlement behavior (Kennedy 1996).

Oysters feed primarily on phytoplankton, but can also feed on smaller zooplankton, detritus, bacteria, and suspended particulates (Langdon et al. 1996). Oysters have also been shown to absorb nutrients directly from the water (Langdon et al. 1996). Studies have shown that increasing carbohydrates or supplementing diets with omega-3 fatty acids can increase oyster growth (Langdon et al. 1996; Jonsson et al. 1999). Furthermore, it has been shown that in an abundance of food, both adult and juvenile oysters will select more nutritious food particles, and reject others (Newell et al. 1996).

Oysters support an important industry. The U.S. National Marine Fisheries Service (NMFS) estimates that the dollar value for oyster landings nationally was $103 million in 2003, $111 million in 2004 and was the 10th ranked marine species in dollar value for 2004 (NMFS 2004). The gulf region led in oyster production with 65% of the national total by weight (NMFS 2004), compared to just 31% in 1980 (LDWF 2004). Louisiana leads Gulf coast production with over 50% of total Gulf coast production (LDWF 2004).

Harvest pressure, disease and pollution have caused oyster fisheries to collapse in many states. In North Carolina, commercial oyster landings are just 2% of the historical peak (NCDMF 2001). The Chesapeake Bay, once the nations leading oyster fishery, now produces less than 1% of its historical peak (Hicks et al. 2004). Pietros and Rice (2003) calculated a thousand fold decrease in Rhode Island's oyster landings since the turn of the 20th century.

Oyster fisheries in New York and New England had collapsed by the early 19th century (Kirby 2004). Kirby (2004) attributes the recent increase in Gulf of Mexico production to demand created by the collapse of other oyster fisheries, and warns that without proper management, Gulf production will soon collapse as well. Besides economic benefits, oyster reefs serve important ecological functions.

Oysters have been described as a keystone species within their habitats (LDWF 2004). As such, they provide a number of essential functions for complex communities of species. These functions include water filtering, recycling biological material, primary productivity, boosting benthic productivity, processing phytoplankton, and providing feeding and nesting habitat for numerous other species (LDWF 2004). Oysters serve to improve water quality by consuming phytoplankton and storing nutrients as biomass, depositing the nutrients to the benthos, or creating high quality protein (gametes and eggs) for other filter feeders (NCDMF 2001; Newell et al. 2004). This leads to reduced turbidity and nutrient load and increased dissolved oxygen, which may in turn stimulate an increase in submerged aquatic vegetation (Newell et al. 2004; Cerco et al. 2005). The oysters role as a habitat for other species makes it extremely valuable to the commercial and recreational fishing industries (NCDMF 2001; LDWF 2004; Street et al. 2005).

Heavily fished oyster reefs lose vertical profile and stability and are more prone to suffocation due to sedimentation (NCDMF 2001). Oyster populations are threatened by over fishing, disease, predation, pollution and habitat destruction (NCDMF 2001; Pietros et al. 2003; Kirby 2004). Decimated oyster populations lose their ability to perform critical ecological functions. Recognizing the value of healthy oyster stocks, both for harvest and for ecological value, many states have incorporated oyster fishery management plans that include restocking oyster cultch with shucked oyster shell (LDWF 2004). However, one common impediment to these plans is an insufficient quantity of shell (LDWF 2004). It was proposed that the same material used in the oysterbreak, could be used as an artificial cultch material.

Bioengineered Concrete

The purpose of this study was to select a suitable material to be used for both the oysterbreak and as an artificial cultch material. The material needed be strong enough to be structurally sound and withstand wave action as well as attract and grow oysters at an acceptably high rate. Anderson (1995) hypothesized that a pH increase due to calcium hydroxide in concrete would increase oyster settlement, and found an increase in oyster settlement beyond that of an increase in pH alone. The Louisiana Department of Wildlife and Fisheries (2004) concluded that crushed concrete attracted more oysters and the mean size of the oysters was larger than oysters grown on crushed oyster shell or crushed limestone. Therefore it was proposed that concrete, combined with a nutrient source will make a superior artificial oyster cultch while maximizing the effectiveness of the oysterbreak.

Concrete consists of aggregates such as sand or stone bound together in a cement matrix. The two main types of cements are hydraulic cements which harden due to hydration reactions and air-set cements which harden through drying. The most commonly used hydraulic cement is Portland cement. A mixture of only cement and water is known as neat cement. Neat cement, combined with fine and coarse aggregates, produces concrete. Coarse aggregates come from gravel, crushed stone, blast furnace slag, and recycled concrete. Aggregates occupy most of the volume of the concrete. Typically, aggregates are stronger than the cement matrix (Kett 2000). The strength of the concrete is based on the strength of the cement matrix, the strength of the aggregates and the strength of the matrix-aggregate interface. Besides water, cement and aggregates, various chemicals known as admixtures can be added to the concrete. These include accelerators, air entraining agents, water reducers, and plasticizers.

Portland cement is made by combining limestone or chalk, gypsum, kaolin, shale or sand and various types of slag. The materials are burned to form a fused mass and ground into the cement powder (Mitchell 2004). The constituents of the cement are very carefully controlled to create certain properties. The five main types of Portland cement are: Type I (general purpose), Type II (moderate sulfate resistant), Type III (high early strength), Type IV (low heat of hydration) and Type V (sulfate resistant) (Kett 2000). Type III cements are designed to reach in 7 days the strength that would be reached at 28 days for other concretes (Artuso et al. 1998). Types II and V are used when the cement will be exposed to sulfur containing waters such as seawater (Mitchell 2004).

The primary components of Portland cement are tricalcium silicate ($3CaO\text{-}SiO_2$), dicalcium silicate ($2CaO\text{-}SiO_2$), tricalcium aluminate ($3CaO\text{-}Al_2O_3$), and tetracalcium aluminoferrite ($4CaO\text{-}Al_2O_3\text{-}Fe_2O_3$) (Mitchell 2004). The strengthening of Portland cement is due primarily to the creation of dicalcium silicate hydrate ($2CaO\text{-}SiO_2 \cdot xH_2O$) as well as some calcium hydroxide salts (Mitchell 2004).

It is generally accepted that Portland cement concretes are susceptible to loss of strength due to exposure to seawater (Bai et al. 2003). The processes of seawater attack include wetting and drying cycles, leaching, temperature variations, corrosion of reinforcing steel, battering by waves and tides, sulfate attack and freeze/thaw cycles (Washa 1998). Proper design can largely control the harmful effects of seawater attack; in fact, mixing clean seawater into a concrete mix will only result in a 8-10% loss in strength (Schutz 1998). Mohammed et al (2004) found that after 20 years in a tidal environment, concrete made from ordinary Portland cement showed no significant decrease in strength. It was speculated that the stability in strength was due to the deposition of Friedel's salt in the void spaces (Mohammed et al. 2004).

Combining water and cement produces what is commonly known as neat cement. Neat cement combined with fine aggregate produces paste. Usually, more water is added to the paste than is necessary to achieve complete hydration of the cement. This is necessary to achieve a practical workability or consistency of the paste, but results in reduced strength for a given amount of cement.

The combination of neat cement with coarse and fine aggregates produces concrete. Approximately 75% of the volume of conventional concrete consists of aggregate (Legg 1998). Aggregates reduce the cost of concrete by reducing the amount of cement needed, and influencing structural characteristics. Coarse aggregate is defined as the aggregate retained on the No. 4 (4.75mm) sieve. Fine aggregate is that which fully passes a 9.5mm sieve, almost entirely passes a 4.74mm sieve and is predominantly retained on a No. 200 (75µm) sieve (Legg 1998). Aggregate comes from gravel, sand, crushed stone, air-cooled blast furnace slag, and recycled concrete. The physical properties of the aggregates affect the properties of the cement. For example, the size of coarse aggregate can affect the strength efficiency, usually defined as ultimate strength per mass of cement per unit volume (Peterman et al. 1986). Smaller coarse aggregates are suitable for high strength concrete, while larger aggregates are suitable for lower strength concretes (Peterman et al. 1986). Increasing the strength efficiency of a concrete reduces cost by reducing the amount of cement needed per unit volume. Texture, water adsorption, mineral composition, strength and density of the aggregates can also affect the concrete (Legg 1998). Lightweight aggregate concrete can be made by substituting pumice, low density porous materials, synthetic lightweight aggregates and even some organic aggregates for crushed rock and gravel (Chandra et al. 2003). These lightweight concretes offer advantages in reduced weight and decreased thermal conductivity.

A type of lightweight concrete can be created by eliminating fine aggregate all together. This type of concrete is known as no-fines concrete. No-fines concretes consist entirely of water, paste and coarse aggregate. They may have a coarse surface texture based on the texture of the aggregate, and a relatively large volume of void space.

Often, other substances need to be added to concrete to enhance performance. Admixtures are materials other than water, aggregate, or cement that are added to concrete. Admixtures are used to modify the properties of concrete such as strength, workability, permeability, rate of hardening, or frost resistance (Schutz 1998). Schutz (1998) describes some of the most common admixtures. Air entraining agents incorporate small, discrete air bubbles into the cement matrix. These air bubbles reduce freeze/thaw damage by reducing pressure caused by water expansion during freezing. Air entraining agents increase the volume of paste per unit of cement used, increase workability and reduce bleeding and permeability. Accelerators increase the rate at which cement hardens. Calcium chloride is the most common accelerator. Other accelerators include soluble chlorides, bromides fluorides, carbonates, thio-cyanates, nitrates, nitrites, formates, silicates, and alkali hydroxides. Water reducing agents decrease water requirements. Many of these also retard the hardening of the concrete. High range water reducers, also known as super plasticizers, do not retard concrete hardening. Because of this, relatively large amounts can be added, resulting in a 20% to 30% reduction in water and a very strong, but workable concrete. Pozzolans are siliceous or siliceous and aluminous materials that, when combined with Portland cement, have cementitious properties. The most common pozzolans are fly ash, silica fume, and high reactivity metakaolin. Pozzolans are used to add volume to the paste, offset poor gradation of aggregates, improve workability, reduce heat generation, reduce thermal volume change, reduce bleeding, and protect from alkali reactive aggregates. Often, combinations of admixtures are used to create the desired properties.

Summary

The use of engineered oyster reefs to combat coastal erosion has been explored. Oysters are gregarious creatures that settle on surfaces based on a complex set of chemical cues. Oysters are filter feeders, and their growth can be enhanced by a diet rich in free fatty acids. Concrete has been shown to be a suitable substrate. Mixing concrete with a product high in free fatty acids, such as cottonseed, may create a highly attractive substrate that enhances oyster growth. Also, mixing concrete with crushed oyster shell may create a very attractive substrate by mimicking some of the natural chemical cues produced by oysters. The addition of organic substances may be deleterious to the strength of concrete. However, if the concrete can meet minimum structural properties, it should be suitable for use in the oysterbreak. The same material may also be useful as an artificial cultch material to replace over harvested cultch stocks and enhance habitat.

OBJECTIVES

In order for the oysterbreak to be successful, it must do two things: 1) support its own weight and the hydrodynamic forces acting upon it and 2) grow oysters at a fast enough rate to achieve full design wave attenuation within a certain time. Based on these criteria, two primary goals were selected for the study. The first goal was to establish a method of analyzing a bio-engineered composite for its structural properties and its ability to attract and grow oysters. The second goal was to use this method to analyze various mixes of concrete and determine an optimal design material that will attract oysters and achieve necessary structural properties.

The first objective was to determine whether there was an increase in oyster growth, measured as a change in perimeter, over time (H_0: $\mu_{5.5\ months} = \mu_{7\ months} = \mu_{9\ months}$).

The second objective was to determine if there was a difference in bulk oyster growth, measured by change in perimeter between different groups of samples (H_{01}: $\mu_{no\ additive} = \mu_{cottonseed}$; H_{02}: $\mu_{no\ additive} = \mu_{oyster\ shell}$; H_{03}: $\mu_{oyster\ shell} = \mu_{cottonseed}$).

The third objective was to determine whether samples with a large amount of cottonseed (>1.5% of total dry mass) had more growth than samples with a small amount of cottonseed (<1.5% of total dry mass) (H_0: $\mu_{<1.5\%} = \mu_{>1.5\%}$).

The fourth and fifth objectives were to apply the tests from objectives two and three to oyster counts and oyster shell measurements.

The sixth objective was to make a qualitative comparison between the perimeter measurements, oyster counts and oyster shell length measurements to determine if perimeter measurement can be used as a proxy measurement for oyster growth.

The seventh objective was to determine if there is a trend in density with respect to cottonseed concentration (H_0: $\mu_{concentration1} = \mu_{concentration2} = \mu_{concentration3} = \mu_{concentration4} = \mu_{concentration5}$).

The eighth objective was to determine if there is a trend in seven day compressive strength with respect to cottonseed concentration (H_0: $\mu_{concentration1} = \mu_{concentration2} = \mu_{concentration3} = \mu_{concentration4} = \mu_{concentration5}$).

The ninth objective was to determine if there is a trend in 28 day compressive strength with respect to cottonseed concentration (H_0: $\mu_{concentration1} = \mu_{concentration2} = \mu_{concentration3} = \mu_{concentration4} = \mu_{concentration5}$).

The tenth objective was to determine the ratio of 28 day strength compared to the 7 day strength.

MATERIALS AND METHODS

Field Tests

A series of trapezoidal concrete beams of varying proportions were made. The beams were made by hand mixing Holcim Type I Portland cement, Quikrete all purpose sand, and #7 size limestone gravel. The mixes were poured into plastic trapezoidal cross- section gutter sections about 76 cm long. Short one inch nominal diameter PVC pipes were placed vertically through the concrete to create holes in either end of the beams. The cement was covered with damp newspaper and a tarp. The PVC pipes were removed after one day, and the samples removed after two days. The samples were transported via pickup truck to the Louisiana State University Sea Grant Oyster Hatchery in Grand Isle, LA. Nylon string was used to tie plastic hooks to the holes in the concrete samples. The samples were suspended from an adjustable long line system approximately 40cm above the bottom in Caminada Bay near Grand Isle, LA in June 2005 (Figure 2).

Some blocks had no additives, some had cottonseed, and some had crushed oyster shell (Table 1). Each block was divided into three segments. For each site assessment, an arbitrary end of the block was selected and measurements taken at 13 cm, 36 cm, and 56 cm from that end. An approximate cross sectional perimeter was determined by wrapping the block with a piece of string and measuring the length of string. The blocks were measured before placement, on November 12, 2005, on January 8, 2006, and on March 8, 2006. Because the blocks were not all the same size, the original values were subtracted from the values on November 12, 2005, on January 8, 2006, and on March 8, 2006 to determine the changes in perimeter. The bases and heights of the trapezoidal cross section were also measured using calipers before placement on January 8, 2006, and on March 8, 2006. An approximate cross sectional area of the concrete bars with oyster growth was calculated using the equation for the area of a trapezoid. The thickness of each bar, from upper surface to lower surface as oriented in water, was also measured (Figure 3 a). The original measurements were, again, subtracted from the measurements on January 8, 2006, and on March 8, 2006 to determine the changes in area and thickness. Oysters were counted by placing a 64 millimeter diameter open circle onto the concrete samples at and counting all oysters that were completely or partially within the circle (Figure 3 b). The oysters were then measured along the longest axis of the shell (known as the shell height) using digital calipers. In most cases, the oyster was measured from the hinge to the bill. In some cases, the oysters grew in such a way that the longest axis of the shell was not from the hinge to the bill. For ease of measurement, these oysters were measured along the longest axis. An arbitrary end of the block was selected and measurements taken at 13 cm, 36 cm and 56 cm from that end. Heavy barnacle encrustation was observed on the bottom of the beams, making it difficult to distinguish individual oysters. Therefore, the bottom was neglected and oyster counts and shell measurements were only taken from the top of the beams.

The following parameters were tested:

1. total increase in perimeter,
2. percent increase in perimeter,
3. increase in cross sectional area,
4. increase in thickness,
5. oyster numbers,
6. and oyster shell measurements.

A Microsoft Excel spreadsheet was created to tabulate the values and compare groups of samples with one tailed students' T test (using the "ttest" function). The following groups were considered:

1. all samples,
2. samples with cottonseed,
3. samples with oyster shell,
4. and samples with neither cottonseed nor oyster shell.

It was observed that concrete containing more than 1.5% of cottonseed to total dry mass sometimes failed to harden properly. Therefore, further comparison was made between samples with less than 1.5% cottonseed and samples with >1.5% cottonseed.

Compression Tests

An array of molds was created by hot gluing 2” (5.1 cm) nominal diameter by 10 cm long schedule 40 PVC pipes to a sheet of sheet steel. This was laid over a ¾” (1.9cm) nominal thickness plywood board of the same dimensions and placed into a plastic bin with a sealable lid. Before assembly, the sheet metal and PVC molds were cleaned thoroughly and inspected for dirt and old concrete. Concrete samples were mixed to a proportion of 1 part Holcim brand Type I Portland cement to 3 parts Quikrete all purpose sand (product 1152) to 2.5 parts Quikrete all purpose gravel (product 1151) by mass. Cottonseed was added to 0%, 0.5%, 1%, 5%, and 10% m/m of cement. Three water contents were tested: 0.7, 0.6, and 0.5 m/m of cement. Six to eight samples were made for each mix (2 tests, 7 days and 28 days, 3-4 samples per test). Samples were hand mixed by first placing the mortar, cottonseed, and water into a clean five gallon bucket. The ingredients were stirred until fully incorporated. The sand was added and incorporated, then the gravel. The concrete mixture was then scooped and hand guided into the appropriate PVC molds. After filling the molds, the mixture was rodded with a half inch diameter steel rod to settle the concrete and remove air pockets. Additional concrete was then added to each mold to fill. After all of the mixes were made and all molds filled, a neat cement cap was made by mixing 3 parts cement to 1 part water (by mass), applying to the top of each sample, and tapping the PVC molds until the surface of the cap was smooth and level. The filled mold array was then covered with plastic wrap, covered with the plastic bin lid, and allowed to cure in an air conditioned lab. After 24 hours, the PVC molds were pulled off of the sheet metal, and the concrete samples removed with a press. The caps were ground to remove irregularities. Each sample was then labeled, wrapped in plastic wrap and placed vertically in the air conditioned lab. At seven days, each sample was carefully measured and weighed.

Table 1. Ratios of concrete ingredients used in field tests.

Sample	1	2	3	4	5	6	7	8
cement	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
water	0.67	0.67	0.50	0.50	0.50	0.67	0.67	0.50
sand	2.58	2.58	1.29	1.29	1.29	2.58	2.58	1.29
gravel	3.87	3.87	0.65	1.29	0.65	0.00	2.58	1.29
cotton seed	0.00	0.00	0.10	0.05	0.05	0.00	0.00	0.03
%cotton seed to total dry mass	0.00	0.00	3.35	1.40	1.70	0.00	0.00	0.70
oyster shell	0.00	0.00	0.00	0.00	0.00	0.31	0.10	0.00
% oyster shell to total dry mass	0.00	0.00	0.00	0.00	0.00	7.97	1.60	0.00

Two strength tests were conducted for each mix, one at 7 days ± 6 hours and another at 28 days ± 20 hours. The tests were conducted with a Quotium Qtest load testing apparatus (Figure 4). The head speed was set to compress at a rate of .13 cm per minute. Because the software only allows a load of up to 44.5 KN, if the load exceeded 44.5 KN, the load and displacement were zeroed, and a second test run without moving the heads. The data sets are then combined in processing. The load vs. displacement curves were exported to tab delimited text files. Stress and strain were computed by dividing the load and displacement by the cross sectional area and length of the samples, respectively. Ultimate stress is defined as the peak

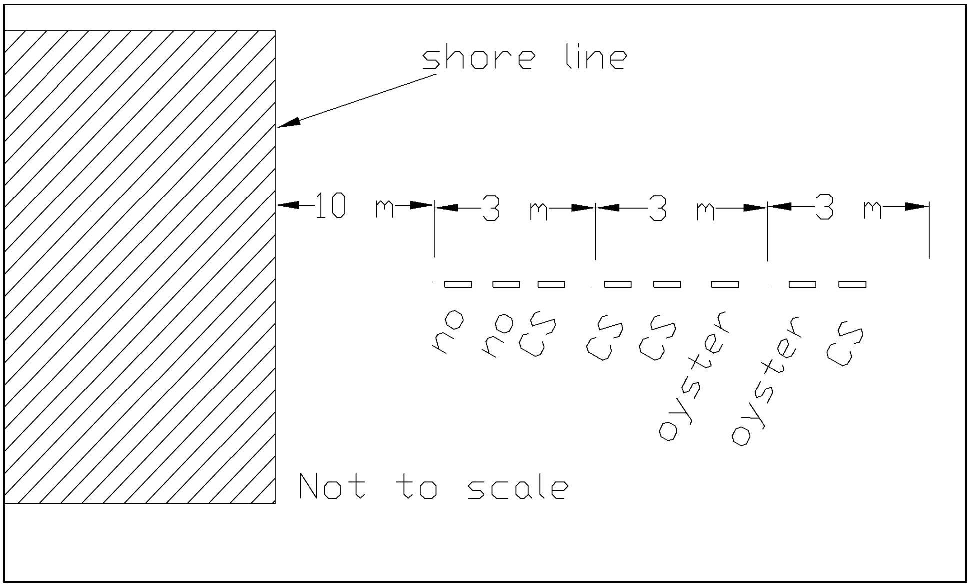

Figure 2: Experimental setup for the field tests. The concrete samples were suspended from an adjustable long line system in Caminada Bay near Grand Isle Louisiana. In this figure, “no” stands for samples with neither cottonseed nor oyster shell. “CS” represents samples containing cottonseed, and “oyster” represents samples containing oyster shell.

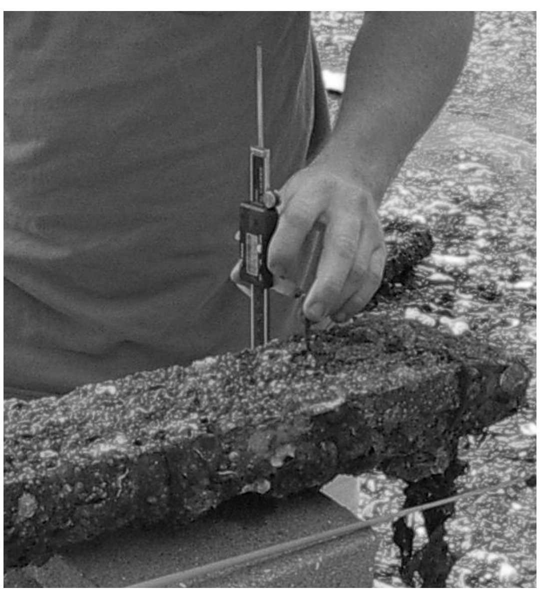

Figure 3 a

Figure 3 b

Figure 3: Measurement of oyster growth on concrete beams. a) Digital calipers were used to measure the height of the beam. b) A 64 millimeter diameter circle was used to estimate the number of oysters per unit area.

stress sustained by the sample. After correcting the strain, a correction factor was applied according to ASTM C 39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. A Microsoft Excel spreadsheet was used to calculate mean values, and 95% confidence intervals. The ratio of 28 day compressive strength to 7 day compressive strength was determined by dividing the mean 28 day strength of each mix by the mean 7 day compressive strength of each mix and computing the mean value and 95% confidence interval of the ratios for the entire data set.

A second group of tests was performed on a series of proprietary low fines (little to no sand) cottonseed enhanced concrete mixes provided by ORA Technologies, LLC (Baton Rouge, LA) (www.oratechnologies.com). These concrete mixes were intended to be used as a material for the oysterbreak or for artificial oyster cultch. Compression tests were performed as described above. Also, mixes were formed in the shape of long trapezoidal beams and subjected to center point load flexure tests (Figure 5). Testing setup and calculation of the modulus of rupture were done according to ASTM C 293-02 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center Point Loading). Concrete samples provided by ORA Technologies, LLC contained one or more of the following admixtures: Glenium 3030 NS (water reducing admixture), Pozzolith® NC 534 (accelerating admixture), and Rheomac® VMA 362 (viscosity modifying admixture), all from Degussa Construction Chemicals (www.degussa.com).

Figure 4: The Quotium Qtest load testing apparatus. This device was used to determine the compressive and flexural strength of concrete samples.

Figure 5. Flexural strength testing.

RESULTS

Field Tests

In November, all of the blocks were observed to be covered with encrusting organisms. However, samples with oyster shell showed an apparent decrease in perimeter. Upon further inspection, it was found that one of the bars was tapered at both ends. This bar was originally measured around the middle. The dimensions of the bar, including oyster growth, were less than the original dimensions at the center. This anomaly was not taken into account during the measurements. In November, samples containing cottonseed had a significantly higher increase in perimeter ($p=.012$) compared to samples with no biological additive (Figure 6, Table 2, Table 3).

In January, both cottonseed and oyster shell treatments had significantly higher increases in perimeter ($p<.001$ and $p=.008$ respectively) than concrete with no biological additive. There was no difference between samples containing cottonseed and samples containing oyster shell ($p=.37$) (Figure 6, Table 2, Table 3).

In March, again, both cottonseed and oyster shell treatments had significantly higher increases in perimeter ($p=.018$ and $p=.005$ respectively) than concrete with no biological additive. However, samples containing oyster shell had a larger increase in perimeter than those containing cottonseed ($p=.049$). Samples containing <1.51% cottonseed by mass were no different than those containing >1.5% cottonseed by mass at all times ($p=.32$, $p=.34$, $p=.47$). Similar results are observed when change in perimeter is measured as a percent of the original perimeter (Figure 7, Table 2, Table 3).

By January, both cottonseed and oyster shell treatments had a larger increase in cross sectional area than concrete with no additive ($p=.062$ and $p=.079$ respectively). There was no significant difference between samples with cottonseed and samples with oyster shell (p=.39) (Figure 7, Table 2, Table 3).

By March, samples with oyster shell had a greater increase in cross sectional area than those with no additive (p=.028). Samples with cottonseed may have had a greater increase than those with no additive (p=.12), though the difference was only slightly significant. Samples with oyster shell may have been larger than those with cottonseed (p=.14), but again, the difference was only slightly significant. At both times, samples with <1.51% cottonseed actually experienced more growth than those with >1.51% cottonseed, though the difference is only slightly significant in January and not at all significant in March. (p=.11 in January, and p=.31 in March) (Figure 8, Table 2, Table 3).

In January, samples containing cottonseed may have had a greater increase in height than those with no additive (p=.11). Samples containing oyster shell had a greater increase in height compared to those with no additive, but not significantly so (p=.22). There was no significant difference between samples with cottonseed and samples with oyster shell (p=.23). There was a slightly significant difference between samples with <1.51% cottonseed, and those with >1.51% cottonseed (p=.15) (Figure 9, Table 2, Table 3).

In March, there was no significant difference between samples with cottonseed and samples with no additive (p=.20). However, samples with oyster shell did have a larger increase in height than those with no additive (p=.08). There was no difference between samples with cottonseed and samples with oyster shell (p=.30) or between samples with <1.51% and >1.51% cottonseed (p=.44) (Figure 9, Table 2, Table 3).

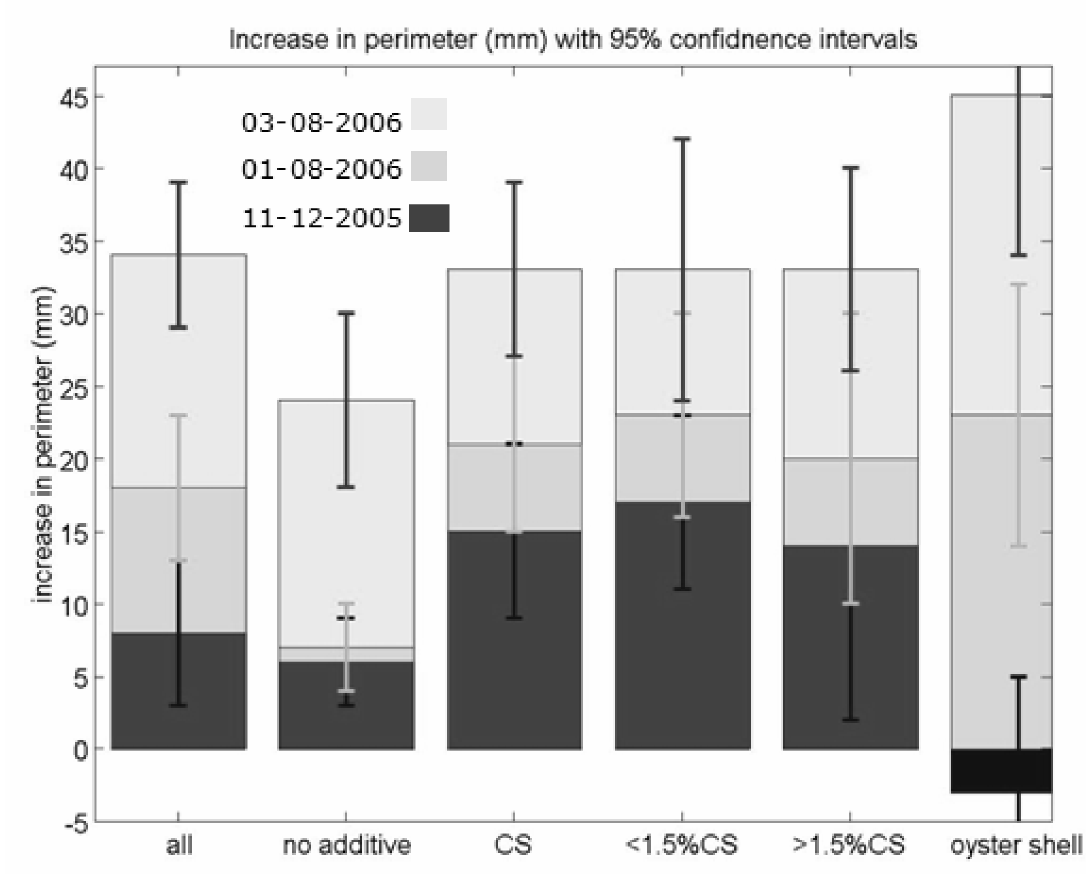

Figure 6: Mean perimeter increase in millimeters with 95% confidence intervals. Here "CS" stands for cottonseed, "all" represents the entire group of samples, and "no additive" groups samples with neither cottonseed nor oyster shell.

Samples with oyster shell had significantly larger oysters (p=.07) than samples with no additive. There were no highly significant differences in shell length between samples with cottonseed compared to samples with no additive (p=.14), between samples with oyster shell and samples with cottonseed (p=.17), and between samples with different amounts of cottonseed (p=.15) (Figure 10, Table 2, Table 3).

Samples containing cottonseed and samples containing oyster shell both had more oysters than those without any additive (p=.05 and p=.03 respectively). There was no difference between samples with oyster shell and samples with cottonseed (p=.28), and between samples with different amounts of cottonseed (p=.45) (Figure 11, Table 2, Table 3).

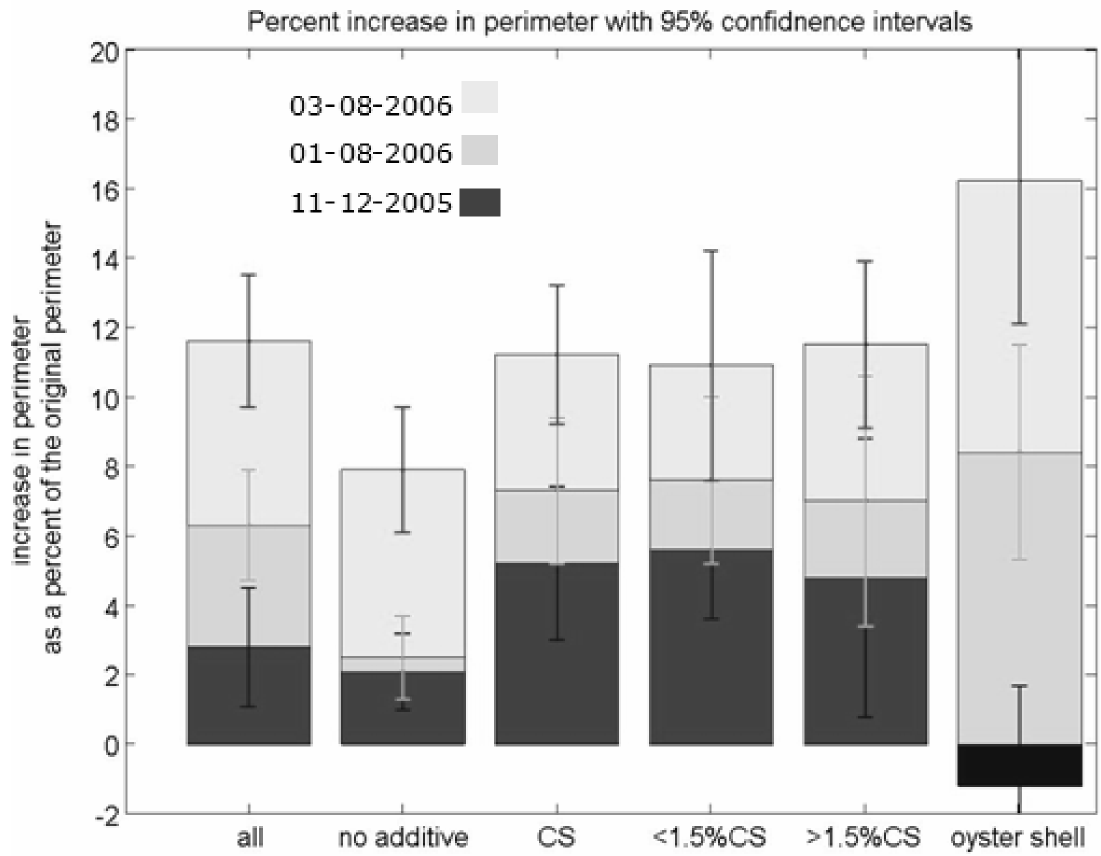

Figure 7: Mean percent increase in perimeter with 95% confidence intervals.

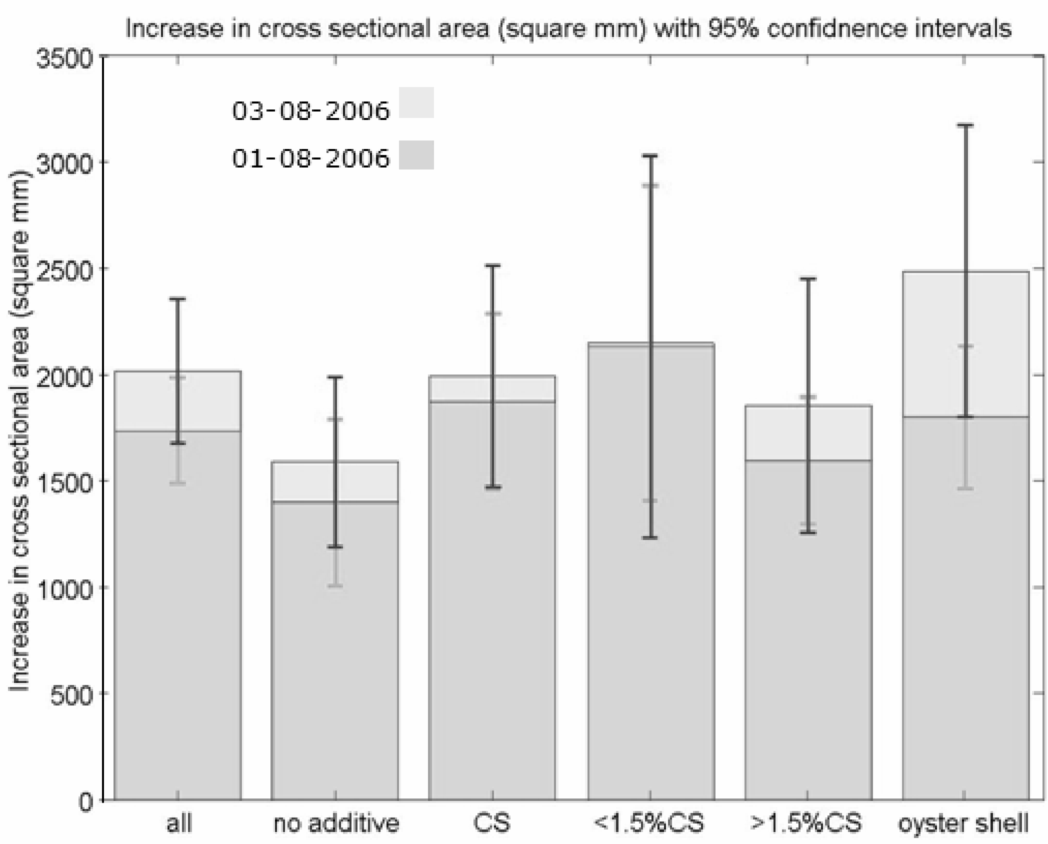

Figure 8: Mean changes in cross sectional area with 95% confidence intervals.

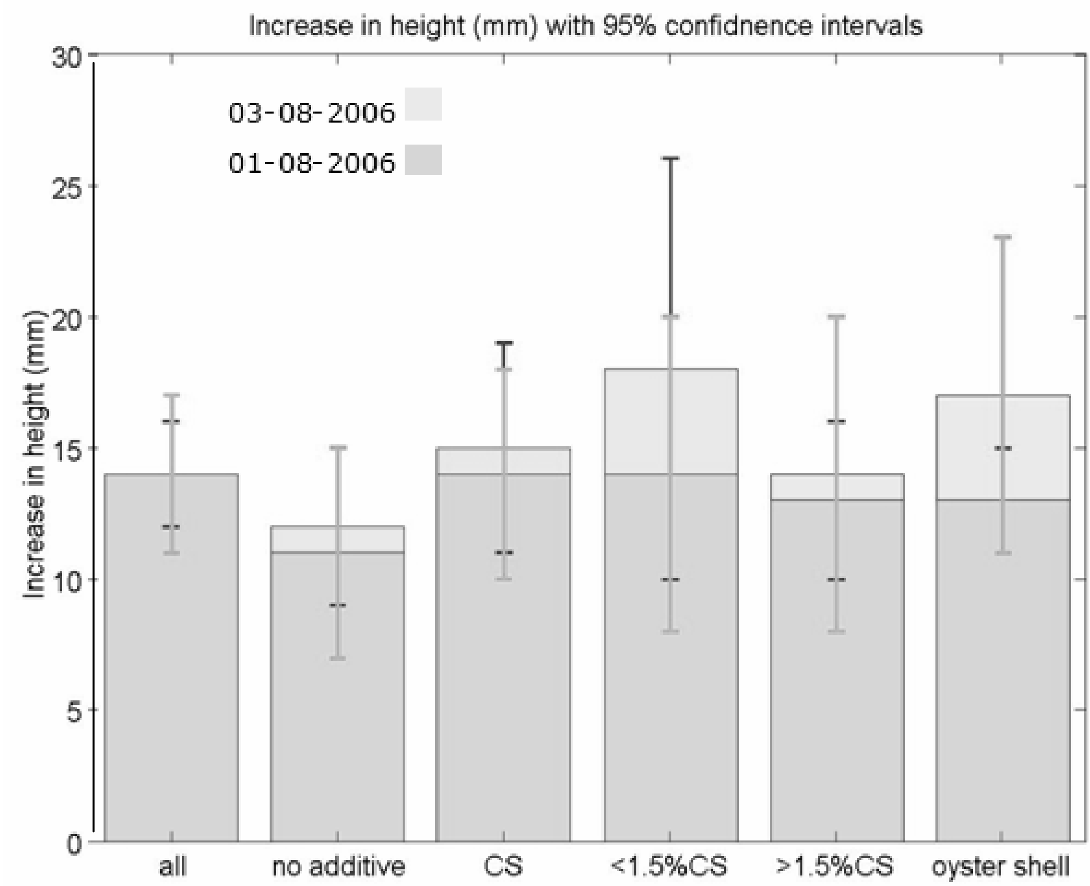

Figure 9: Mean increase in height with 95% confidence intervals.

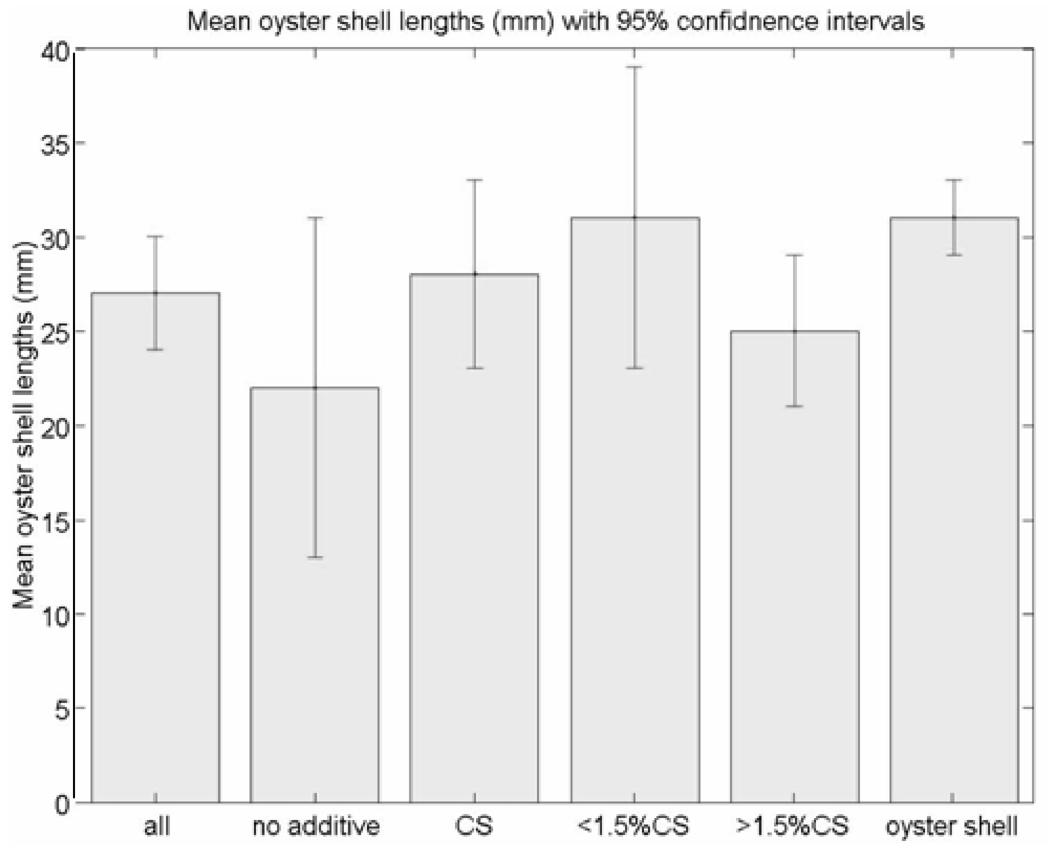

Figure 10: Mean oyster shell length in mm with 95% confidence intervals.

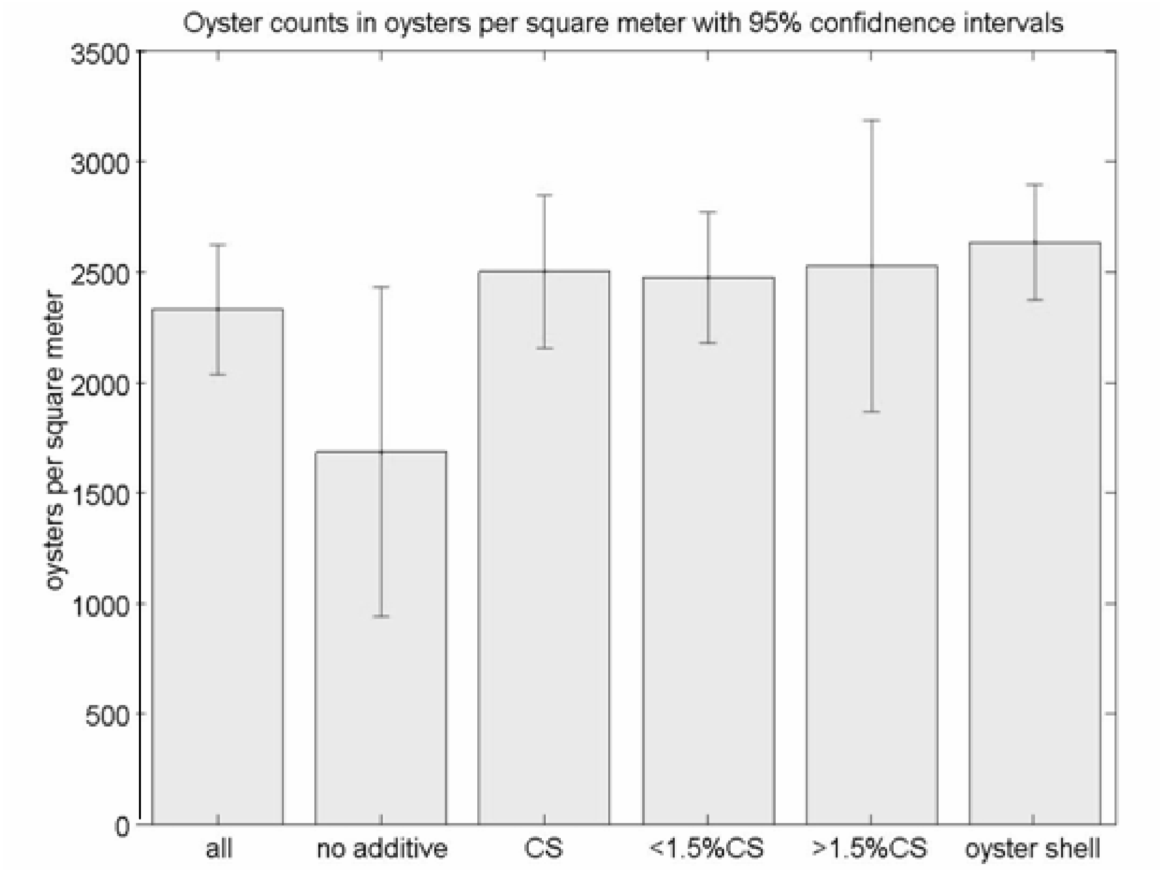

Figure 11: Mean oyster counts in oysters per square meter with 95% confidence intervals.

Table 2: Summary of field test measurements.						
	Mean change in perimeter (mm)	**Mean change in perimeter as a percent of original perimeter**	**Mean change in area (mm^2)**	**Mean change in height (mm)**	**Mean oyster shell max dim (mm)**	**Mean oyster counts in oysters per square meter**
12-Nov-05						
All	8	2.8				
No additive	6	2.1				
CS	15	5.2				
<1.5% CS	17	5.6				
>1.5% CS	14	4.8				
Oyster shell	-3	-1.2				
8-Jan-06						
All	18	6.3	1734	14		
No additive	7	2.5	1398	12		
CS	21	7.3	1871	15		
<1.5% CS	23	7.6	2147	18		
>1.5% CS	20	7.0	1595	13		
Oyster shell	23	8.4	1798	13		
8-Mar-06						
All	34	11.6	2014	14	27	2328.8
No additive	24	7.9	1589	11	22	1684.075
CS	33	11.2	1992	14	28	2499.8
<1.5% CS	33	10.9	2129	14	31	2473.5
>1.5% CS	33	11.5	1854	14	25	2526.1
Oyster shell	45	16.2	2484	17	31	2631.4

Table 3: Summary of one-tailed student's T test comparing different groups of samples.						
	Mean change in perimeter (mm)	**Mean change in perimeter as a percent of original perimeter**	**Mean change in area (m^2)**	**Mean change in height (mm)**	**Mean oyster shell max dim (mm)**	**Mean oyster counts in oysters per square meter**
12-Nov-05						
Cottonseed vs. no additive	0.012387	0.0123				
oyster shell vs. no additive	0.034159	0.0377				
Oyster shell vs. Cottonseed	0.002071	0.0026				
<1.5%CSvs. >1.5 % CS	0.318879	0.3636				
8-Jan-06						
Cottonseed vs. no additive	0.000622	0.0006	0.0624	0.10609		
oyster shell vs. no additive	0.007751	0.0058	0.079	0.2208		
Oyster shell vs. Cottonseed	0.369793	0.2851	0.3962	0.22958		
<1.5%CSvs. >1.5 % CS	0.344481	0.3898	0.1093	0.1511		
8-Mar-06						
Cottonseed vs. no additive	0.018308	0.0148	0.1229	0.19574	0.14124	0.045415
oyster shell vs. no additive	0.004971	0.0044	0.0288	0.07705	0.06611	0.027602
Oyster shell vs. Cottonseed	0.048937	0.0336	0.1429	0.30035	0.17458	0.27961
<1.5%CSvs. >1.5 % CS	0.472822	0.3902	0.3146	0.43836	0.14816	0.445233

Compression Tests

Concrete density ranged from 2.25 grams per cubic centimeter (g/cm^3) for no cottonseed to 2.05 g/cm^3 at high levels of cottonseed (Figure 12). Strength ranged from 27 megapascals (MPa) to 7 MPa for high levels of cottonseed (Figure 13). Above about 1.5% cottonseed to total dry mass of ingredients, the concrete often failed to harden and, therefore, was not included in the data. Twenty-eight day compressive strength ranged from about 27 MPa to a low of about 9 MPa (Figure 14). The ratio of 28 day compressive strength to 7 day compressive strength for all samples was 1.1 ±0.1 with 95% confidence.

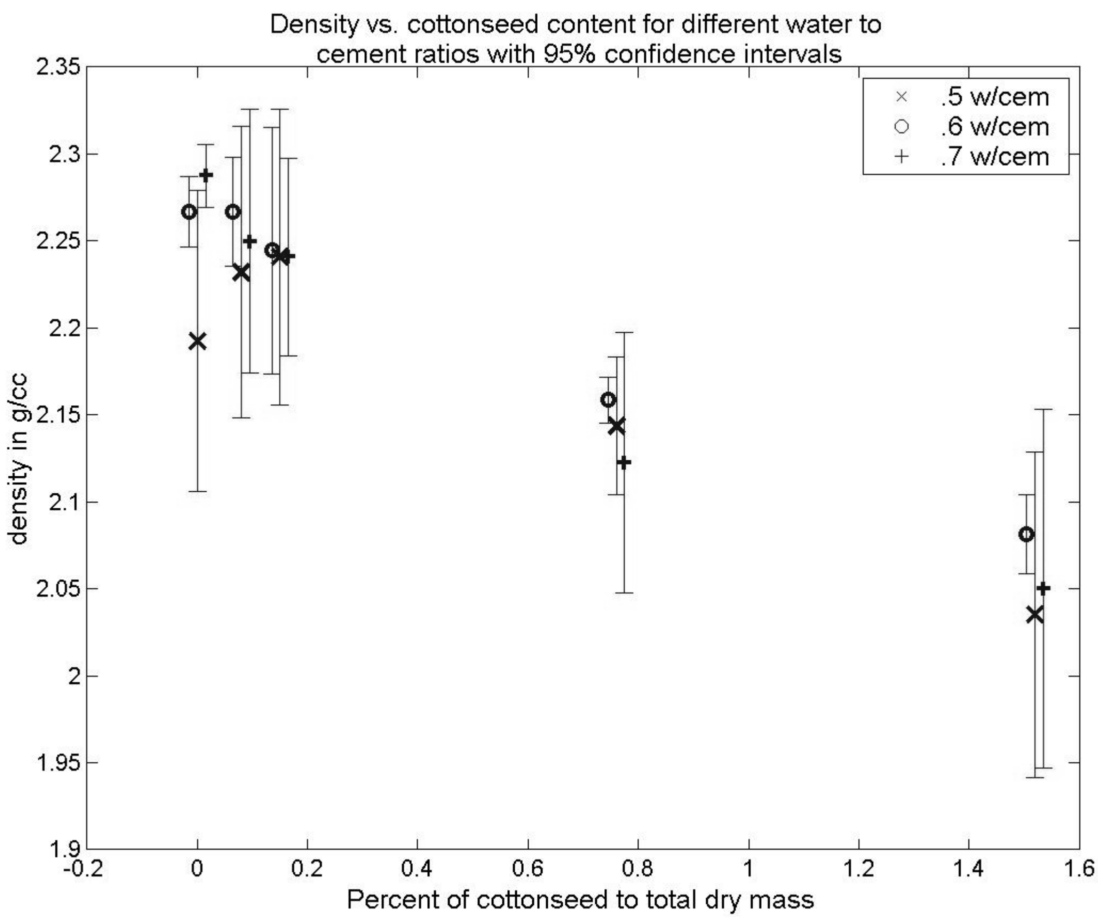

Figure 12: Density vs. cottonseed content for different water to cement ratios.

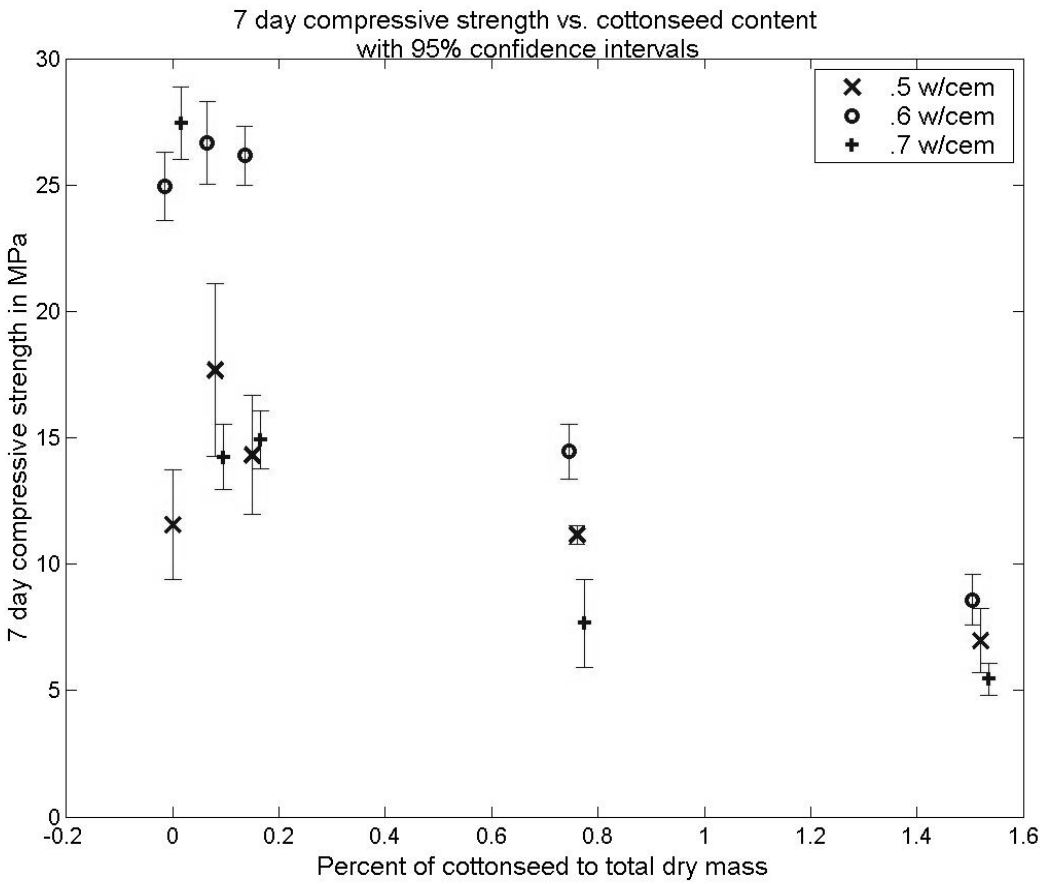

Figure 13: Seven day compressive strength vs. cottonseed content for different water to cement ratios.

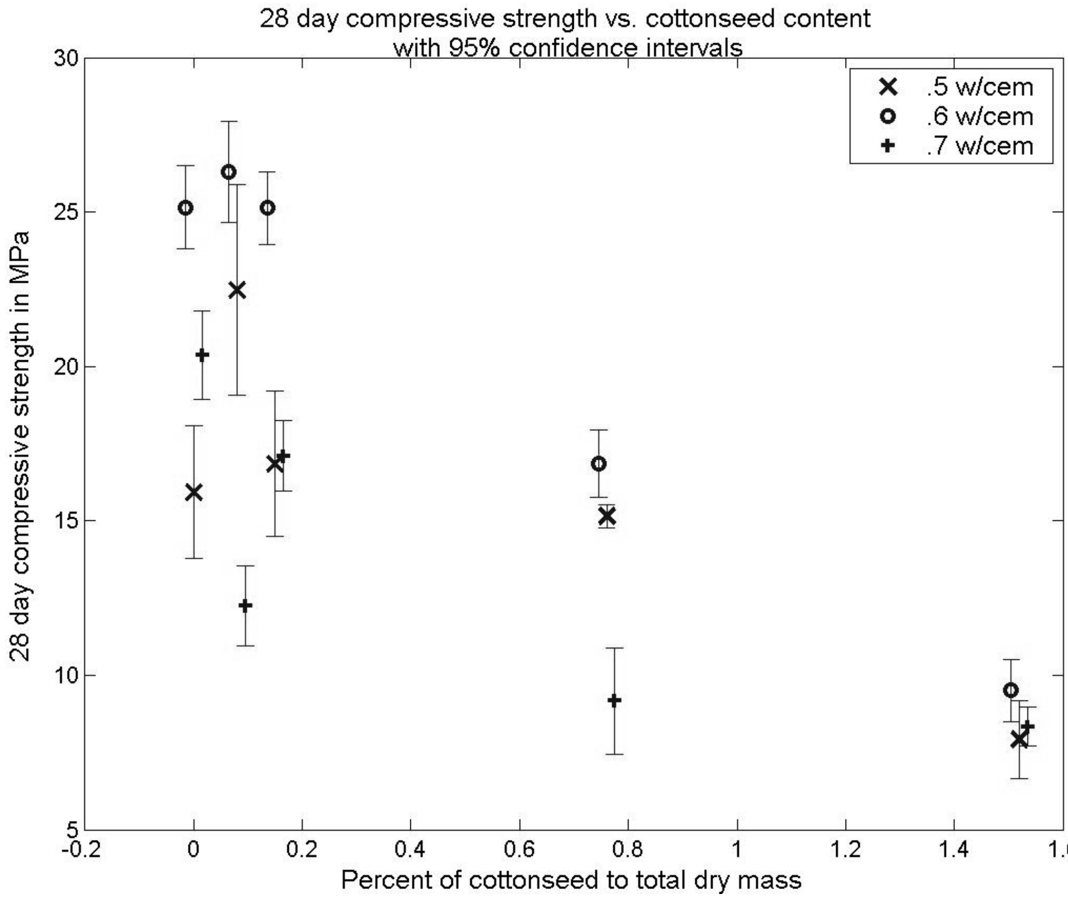

Figure 14: Twenty eight day compressive strength vs. cottonseed content for different water to cement ratios.

Compressive strength for samples from ORA Technologies, LLC ranged from about 26.1 MPa for OC4 to about 11.3 MPa for NF (Figure 15). Flexural strength ranged from about 6.2 MPa for OC4 to about 3.7 MPa for NF (Figure 16). The ratios between the two ranged from a remarkable high of .45 for OC1 to a more expected value of .26 for OC4 with a mean of 0.33±.06 at 95% confidence (Table 4). OC2f showed a relatively high flexural strength to compressive strength ratio (.34±0.07 with 95% confidence). The seven day compressive strength is about two times the 24 hour compressive strength (2.1+-0.1 times, 95% confidence).

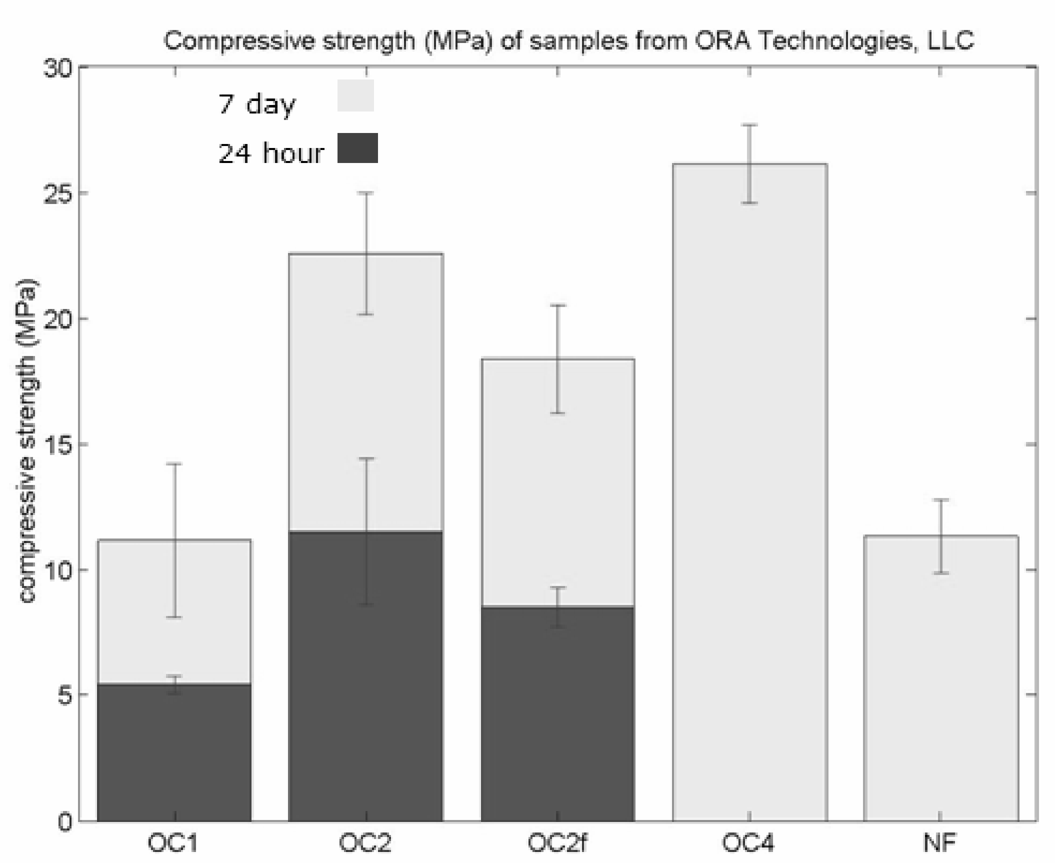

Figure 15: Ultimate compressive strength of samples provide by ORA technologies. Samples were roughly twice as strong in 7 days as at 24hrs. OC4 and NF were not tested at 24 hours.

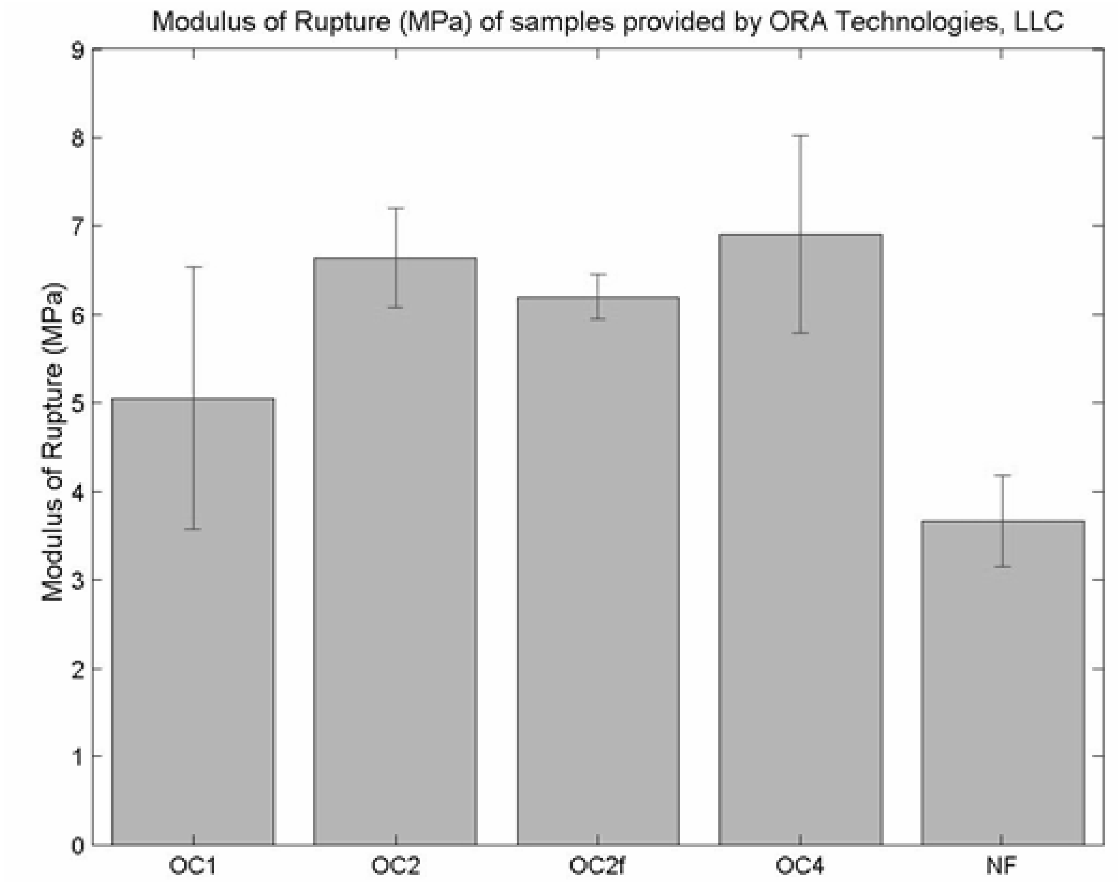

Figure 16: Flexural strength (modulus of rupture) of samples provided by ORA Technologies.

Table 4: Strength measurements for ORA Technologies proprietary mixes.

Sample		24 hr compressive strength (MPa)	7 day compressive strength (Mpa)	Modulus of rupture (Mpa)	Ratio of 7 day compressive strength to modulus of rupture
OC1	**mean**	5.44	11.16	5.05	0.45
	stdev	0.30	2.70	1.30	
OC2	**mean**	11.51	22.54	6.63	0.29
	stdev	2.57	2.13	0.49	
OC2f	**mean**	8.53	18.35	6.19	0.34
	stdev	0.69	1.90	0.22	
OC4	**mean**		26.09	6.90	0.26
	stdev		1.36	0.99	
NF	**mean**		11.33	3.66	0.32
	stdev		1.28	0.45	

DISCUSSION

In nearly every measurement, samples containing cottonseed or oyster shell experienced more oyster growth than those with no additive. Initially, the samples containing oyster shell appeared to have less growth due to the tapering of the beams containing oyster shell. After some time, despite tapered bars, the samples containing oyster shell showed more growth than those containing cottonseed, though the difference was not always statistically significant. This may indicate that the oyster shell containing concrete produces oysters at a much higher growth rate than concrete with cottonseed. The caliper measurements involved the greatest use of judgment, and therefore were the most subjective. If we disregard the caliper measurements, and just look at the perimeter measurements, then by March oyster shell concrete stimulated significantly more oyster growth than cottonseed containing concrete ($p=.05$ for total change in perimeter, and $p=.03$ for percent increase in perimeter). However, oyster counts, and shell length measurements do not support this.

It was observed that in March, the bars containing oyster shell and some of the bars containing cottonseed suffered very heavy predation from oyster drills (Figure 17). This may have led to a significant underestimation of oyster growth than observed. No oyster drills were observed in January, probably due to lower water temperatures. If this is the case, then predation will likely increase in the coming warm months, thus further skewing future results. There appeared to be no increased growth with additional levels of cottonseed, indicating that the concentration of cottonseed to total dry mass need not exceed 1.5% to have a significant effect on oyster growth. Above about 10% cottonseed to cement, or about 1.5% to total dry mass, the concrete often failed to harden and, therefore, was not included in the strength data. More data is needed to determine the growth characteristics of concrete with lower levels of cottonseed.

Figure 18 shows compressive strength and perimeter increase due to oyster recruitment with increasing levels of cottonseed. There appears to be no advantage to increasing cottonseed content to levels that adversely affect strength. Further tests may be necessary to determine oyster recruitment at very low levels of cottonseed (<0.5%). However, if we assume a linear relationship between cottonseed content and perimeter increase due to oyster growth below 0.7% cottonseed, then using concrete with 0.5% cottonseed will provide for enhanced oyster growth and still achieve a compressive strength of 20 MPa. If we assume a perfectly linear relationship between cottonseed content and density in Figure 3.1, then concrete with 0.5% cottonseed will have a density of approximately 2.2 g/cm^3.

Figure 17: Predation. In March, the oysters suffered from very heavy predation due to oyster drills. Large numbers of oyster drills were observed on some of the samples. Predation may have led to an underestimation of oyster growth.

The concrete from ORA Technologies had a relatively high flexural strength to compressive strength ratio (Table 4). This indicates that using a conservative estimation (20-25%) we can predict, for design purposes, the flexural strength of the concrete based on compression tests. Based on this estimation, we can predict flexural strengths of 5.5-6.9 MPa for regular concrete to 1.4-1.7 MPa for concrete with very high levels of cottonseed.

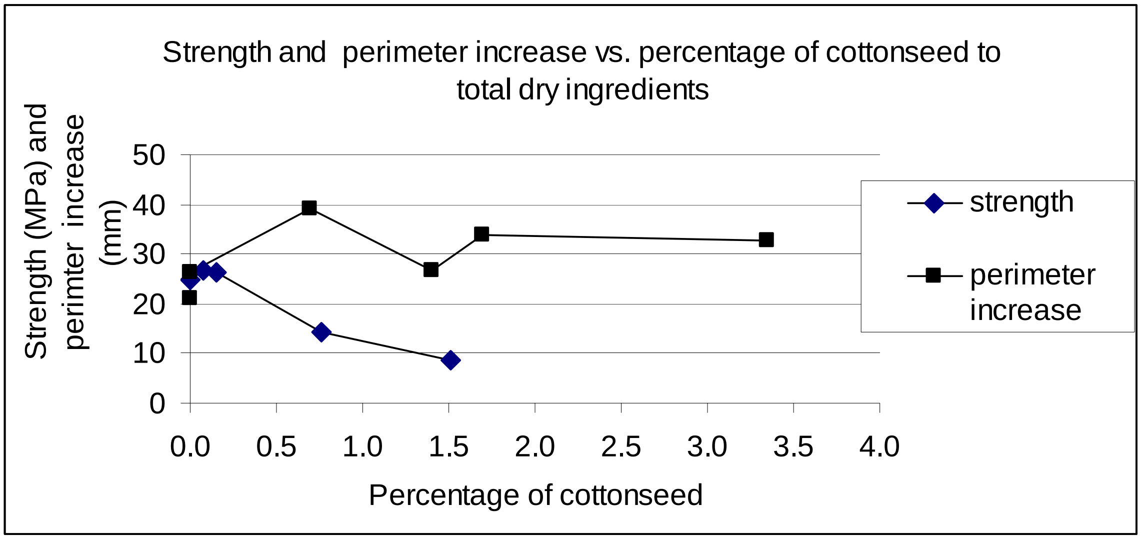

Figure 18: Compressive strength and perimeter increase compared to the percent of cottonseed to total dry ingredients.

For comparative purposes, the concrete beam height measurements at nine months in Table 2 were converted to rates in units of centimeters per year. These values were then inputted into the Campbell (2004) model for predicting wave attenuation with time. The model was run using these values and an arbitrary oysterbreak geometry (Figure 19). An oysterbreak constructed of standard concrete reached its full effectiveness in about 1300 days (3-4 years). An oysterbreak constructed of concrete with cottonseed reached its full effectiveness in about 1000 days (<3 years). The most rapid reduction in wave height was predicted for an oysterbreak made with concrete containing oyster shell. Such an oysterbreak was predicted to reach maximum effectiveness in about 800 days (about 2 years).

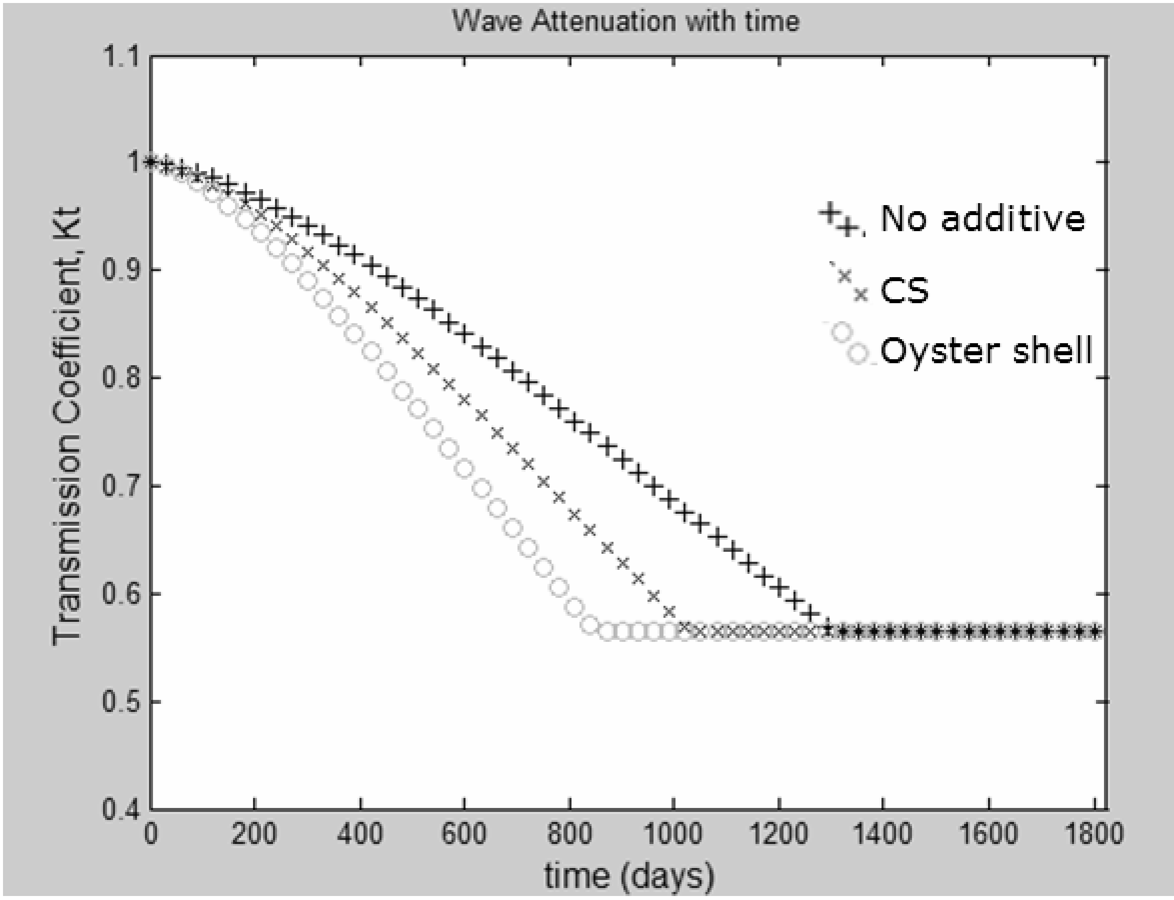

Figure 19: Wave transmission number with time. The Campbell (2004) model for predicting oysterbreak performance with time was used to compare the performance of oysterbreaks made form concrete with no additives, concrete with cottonseed, and concrete with oyster shell.

Calculations were performed to determine the stresses on individual hexagonal units (Figure 1) made from concrete with varying amounts of cottonseed. The masses of hexagonal units were determined by multiplying the densities of the different concretes by the volume of an individual hexagonal unit. The compressive stress at the bottom of a stack of hexagonal units, 6 units tall was calculated by dividing the mass of the 6 units by the area of the face of the hexagonal unit. In all cases, the compressive stress was less than 1 MPa which is less (by orders of magnitude) than the lowest ultimate strength found in this study.

Concrete is very strong in compression, but weak in tension or flexure. This is the reason that reinforcing bar is often added to concrete beams. The flexural strength of concrete (measured as the modulus of rupture) is typically about 20% of the compressive strength (Washa 1998). In order to determine if a beam made of the concrete used in this study could support its own weight, the equation for the modulus of rupture was solved for maximum sustainable load under a given geometry. The modulus of rupture equation found in ASTM C 293-02 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center Point Loading) uses the maximum applied load in Newtons and the geometry of the specimen as variables. An approximate modulus of rupture was calculated by multiplying 20% times the 7 day compressive strengths of the concrete samples. Hypothetical beams with dimensions of 1828.8mm long x 152.4mm x 152.4mm were considered. The equation for modulus of rupture was solved for the maximum sustainable load in Newtons, and then this value converted to mass in kilograms. The maximum sustainable mass was between 1.5 and 8 times the total mass of the beams (Table 5). This method assumes that the mass of the beams is a point load at the centroid rather than a distributed load. The beams are supported at the ends, and buoyancy in water is neglected. It should be noted that the modulus of rupture used here is only 0.2 times the 7 day compressive strength, whereas flexure tests for the samples provided by ORA Technologies, LLC indicated a flexural strength of 0.29 to 0.45 times the 7 day compressive strength. These factors indicate that the maximum sustainable masses indicated in Table 5 are conservative, and that even the weakest concrete in this study could support its own weight.

Table 5. Maximum sustainable masses and actual masses of hypothetical concrete beams.

Mass of Beam (kg)	estimated R (MPa)	Maximum sustainable mass
93	2	304
96	5	656
97	5	722
95	4	465
96	5	701
96	3	374
95	3	377
95	5	688
95	3	393
91	2	294
92	3	380
90	2	201
86	1	184
88	2	226
87	1	144

CONCLUSIONS AND FUTURE WORK

The purpose of this study was to evaluate concrete with various biological additives for its structural properties and ability to attract and grow oysters. There was a large decrease in compressive strength (about 75%) at high levels of cottonseed (~1.5%). However, even at lowest strength found in this study, a concrete beam would support its own weight and nominal water forces. The oyster growth measurements and oyster counts suggest that this level of cottonseed is not necessary to achieve enhanced oyster growth. It was concluded that cottonseed enhanced concrete can produce a structurally sound material that enhances oyster growth. It was also concluded that concrete containing oyster shell will enhance oyster growth, though the structural properties of such a concrete have not been determined.

The model developed by Campbell (2004) was used to predict and compar the performance of oysterbreaks made from standard concrete and biologically enhanced concrete. Further studies will be needed to determine the mechanical properties of oyster shell enhanced concrete. Because both cottonseed and oyster shell tended to enhance the concrete's ability to grow oysters, availability and price may be governing factors in selecting cottonseed or oyster shell. Further testing is needed to determine the biomass of oysters on the concrete samples. Studies to determine oyster growth on concrete enhanced with both oyster shell and cottonseed are also recommended. More data needs to be collected to determine the oyster growth properties of concrete with very small (<0.5%) amounts of cottonseed.

Besides properties of the material itself, some other criteria should be addressed in the design of the oysterbreak, or deployment of artificial oyster cultch. The materials should be deployed to coincide with the spring oyster spawning. Factors related to the location of the project need to be considered in order to maximize the accumulation of biomass. These include temperature, salinity, predation pressure, oyster disease, natural spat levels, and other species.

Deploying the oysterbreak in areas with low natural spat levels may require seeding of the material. Also, a method should be developed for eliminating or reducing predation on the reefs. In designing the oysterbreak, factors such as the length, width, height, depth, and distance from shore should be optimized to achieve the desired wave attenuation characteristics. Local hydrodynamic conditions and expected oyster growth will influence these variables. If used as a harvestable oyster cultch, the material should maintain vertical relief, and separate easily for the selection of individual oysters.

Besides shore protection and harvestable cultch, this material could be used to create permanent reefs for ecological and fisheries enhancement. The oysterbreak could be used in tandem with traditional coastal engineering techniques such as beach nourishment and vegetative plantings. Oysters have been known to colonize the fringes of *Spartina* marshes (NCDMF 2001). Perhaps biologically enhanced concrete could be used to stabilize the edges of a *Spartina* marsh. Biologically enhanced concrete could also be used in some sort of a aquaculture operation to quickly grow oysters or other shellfish.

Data indicated that materials including cottonseed or oyster shell may enhance oyster growth and still provide sufficient strength to be useful in design and deployment of artificial reefs and other applications.

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VITA

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